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Loading dose of physical activity is related to muscle strength and bone density in middle-aged women

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ABSTRACT

The aim of the current study was to investigate the association between loading dose of physical activity, muscle strength and bone density in middle-aged women. Thirty four healthy women (mean age = 49.8 ± 7.5 years) were recruited. They were requested to wear an accelerometer for a period of 10 h (from 9 am to 7 pm) on a day to record the acceleration. On a separate day their knee extension torque (KET) was measured using an isokinetic dynamometer and broadband ultrasound attenuation (BUA) at the heel by an ultrasound bone scanner. The loading dose of physical activity was calculated at four intensity categories — very light, light, moderate, and vigorous (intensities of <5 BW/s, 5–10 BW/s, 10–15 BW/s and >15 BW/s) and for three frequency bands — 0.1–2 Hz, 2–4 Hz, and 4–6 Hz. Correlation analysis was used to examine the association between loading dose and age, KET, and BUA. With the increase of age, there tended to be a decrease in the loading dose of vigorous activity in 2–4 and 4–6 Hz frequency bands (Kendall's tau = −.22, $p < .1$). The increase of loading dose in all three frequency bands in moderate or vigorous activity was associated with higher BUA (Kendall's tau = .27–.41, $p < .05$). The increase of loading dose in all frequency bands in light, moderate, or vigorous activity was associated with higher KET (Kendall's tau = .30–.45, $p < .05$). It is concluded that physical activity, especially that at high intensity level and high frequency range, may have beneficial effect on muscle strength and bone density in middle-aged women.

Introduction

An essential aspect of health and wellbeing throughout an individual's lifespan is the well functioning of the musculoskeletal system to provide an efficient instrument for locomotion, support and protection. Mechanical loading from physical activity is a key determinant of the growth and maintenance of the musculoskeletal system. Bone and muscle can increase their mass and strength rapidly in response to mechanical loading during the early years through the process of modelling. Peak mass and strength are usually attained around the second and third decade [1]. However, with the ageing process there is a decline in musculoskeletal health in both men and women [2]. The primary musculoskeletal changes reported with ageing include a decline in skeletal muscle mass, strength and size [3], together with a net loss of bone mineral density, bone mineral content, bone structure and strength [4].

Wilmore [5] advocates that primary musculoskeletal regressions start to develop around the third and fourth decade. However, musculoskeletal diminution is not linear and does not occur at the same rate and age in men and women. Evidence supports that musculoskeletal structure and function decline at a faster rate among middle-aged women, which is related to the drop in oestrogen levels during menopause [6]. It is therefore advised that preventive measures should be taken early in order to prevent the development of osteoporosis and sarcopenia in pre- and postmenopausal women [7–9].

Physical activity has been widely recommended as an effective intervention for the conservation of musculoskeletal health among pre- and postmenopausal women [7–9]. However, the effectiveness of this intervention is largely dependent on the extent to which mechanical loading is applied to bone and muscle. Therefore it is essential to objectively assess the mechanical loading induced by physical activities. To achieve this, it is necessary to develop assessment method that can accurately measure the parameters that are determinants for bone and muscle adaptation, such as intensity, frequency (rate), and dose of mechanical loading [10]. It is also important that the loading of physical activity can be assessed in natural environment to provide comprehensive information on mechanical loading.

Our latest research has developed a novel method that can objectively assess loading intensity of physical activity in a non-laboratory environment [11]. Using a miniature accelerometer attached to the trunk, loading intensity can be derived from the magnitude and frequency of the signals. Our research shows that the method is able

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to discriminate the loading intensities of different physical activities and to look the intensities in different frequency spectra. One major attraction of this method is that it is non-intrusive and can monitor activities throughout the day, or over a long period of time.

The aim of this study was to investigate the association between the loading of physical activity and muscle strength and bone density in middle-aged women by using this method.

Methods

Participants

Thirty four healthy women with average age of 49.8 years (SD: 7.5 years) were recruited. All of the participants were members of a local fitness centre, and exercised at least twice a week in or outside the centre. The average weight, height, and body mass index (BMI) of participants were 62.5 kg (SD:7.3), 1.62 m (SD: 0.07), and 23.8 kg/m^2 (SD:3.2) respectively. Inclusion criteria were that the participants were non-smoker, free from musculoskeletal injuries or disability, and were physically fit and able to participate in the study. The study was approved by the University's ethical committee. All participants gave written informed consent before participating in the study.

Measurements

Physical activity

A miniature (size 39 × 23 × 72 mm; weight 16 g) three-axis accelerometer (model 145B, MSR Electronics GmbH, Switzerland) was used to measure acceleration during physical activity. The device was programmed to record the acceleration at a sampling rate of 20 Hz for a period of 10 h (from 9 am to 7 pm) in a weekday. It was securely attached by double sided tape onto the skin of lower back at the level of L5. Participants were instructed to carry on with their normal daily activities during the course of recording. The accelerometer was collected after the recording finished. The data was then extracted and processed.

Quantitative ultrasound of the heel

An ultrasound bone scanner (McCue Cuba Clinical Machine Version 2.6, Hampshire, England) was used to measure the broadband ultrasound attenuation (BUA) of calcaneus (heel bone) on the right foot.

Dynamic knee extension torque

Dynamic knee extension torque was measured on right leg by using an isokinetic dynamometer (Cybex Norm, Computer Sports Medicine Inc., Stoughton, MA, USA). Participants were strapped in a seated position of 85° with adjustable belts around the chest, thigh and ankle. The rotation axis of the dynamometer was aligned with the lateral condyle of the knee joint. The range of motion was set between 75° knee flexion and full knee extension. Knee extension torque was tested on right leg at angular velocity of 60 º/s. Before commencing the test, participants underwent a 5-minute warm-up session of light jogging. They then completed a familiarisation set of 5-repetition dynamic knee extension at 60°/s. After 1 min of recovery, participants performed the test set of 5-repetition dynamic knee extension at 60°/s. They were asked to put their maximum effort during the test set. The peak torque values from the 5 contractions in the test set were averaged to obtain the knee extension torque.

Data analysis

The recorded 10-hour raw acceleration data were exported to computer by using the MSR software (MSR 4.16). The data were then analysed by a customised MATLAB programme (version 7.10.0, R2013a; the Mathworks, Inc, Natick, Massachusetts, USA). This customised programme performed the following data analysis: firstly, the resultant acceleration was computed, and was then filtered using a Butterworth bandpass filter (0.1 to 6 Hz) to remove the static gravitational acceleration and noise [11]. The resultant acceleration data were then divided into 7200 consecutive segments, with a length of 5 s each. Fast Fourier transformation was performed on each segment to obtain its Fourier series in frequency domain. The loading intensity [normalised to body weight (BW)] of physical activity at each segment was then calculated as [11]:

$$LI = \sum_{f_i=0.1}^{6Hz} \frac{(A_i \times f_i)}{g} \tag{1}$$

where LI is the loading intensity (BW/s), f_i is the ith frequency in the Fourier series (Hz), A_i is the acceleration (m/s^2) at frequency f_i, and g is the gravitational acceleration (9.81 m/s^2). The loading intensity at each segment was also calculated over three frequency bands: 0.1–2, 2–4, and 4–6 Hz:

$$LI\_B1 = \sum_{f_i=0.1}^{2\mathrm{Hz}} \frac{(A_i \times f_i)}{g} \tag{2}$$

$$LI\_B2 = \sum_{f_i=2}^{4\mathrm{Hz}} \frac{(A_i \times f_i)}{g} \tag{3}$$

$$LI\_B3 = \sum_{f_i=4}^{6\mathrm{Hz}} \frac{(A_i \times f_i)}{g} \tag{4}$$

where *LI_B1*, *LI_B2*, and *LI_B3* are loading intensities at frequency bands 0.1–2, 2–4, and 4–6 Hz, respectively. The use of these three frequency bands was based on previous findings that the effect of loading frequency on osteogenesis was different at frequencies from these bands (e.g., 1 Hz and 5 Hz) [12].

Each of the 7200 segments was then assigned into four categories according to its loading intensity (*LI*) — very light (less than 5 BW/s), light (5–10 BW/s), moderate (10–15 BW/s), or vigorous (over 15 BW/s). According to our previous research [11], typical activities in these categories include: very light (less than 5 BW/s) — slow walking, normal walking, and ascending and descending stairs; light (5–10 BW/s) — fast walking; moderate (10–15 BW/s) — slow running and normal running; vigorous (over 15 BW/s) — fast running. For each category, the duration of physical activity spent in this category was calculated by multiplying the number of segments within this category with the duration of each segment (5 s). The loading dose at each category was also calculated over the three frequency bands:

$$LD\_B1 = \ln(1 + \sum_k 5 \times LI\_B1) \tag{5}$$

$$LD\_B2 = \ln(1 + \sum_k 5 \times LI\_B2) \tag{6}$$

$$LD\_B3 = \ln(1 + \sum_k 5 \times LI\_B3) \tag{7}$$

where *LD_B1*, *LD_B2*, and *LD_B3* are loading dose at frequency bands 0.1–2, 2–4, and 4–6 Hz, respectively, and k is the number of segments in a specific intensity category.

The participant's BUA and knee extension toque were normalised to their body weight. Friedman's ANOVA was employed to examine the difference in the duration of physical activity spent in different intensity categories. Pearson's correlation analysis was employed to examine the relationship among age, BUA and knee extension torque. Non-parametric correlation analysis (Kendall's τ) was used to examine the relationship between loading dose and age, BUA, and knee extension torque. SPSS (version 21.0, Inc, Chicago, IL) was used for statistical analysis. Significance was accepted at $p < .05$.

Results

The duration of physical activity was significantly different among the four intensity categories, $p < .001$ (Table 1). The median value showed that about 99% of the 10-hour recording time was spent on physical activity with very light intensity. The time spent on moderate and vigorous activities was generally very short, with large variation among participants, ranging from 0 to 387 s for moderate activity, and from 0 to 1755 s for vigorous activities. Of the 34 participants, 15 did not have any moderate activity recorded, while 19 did not have any vigorous activity.

There was a significant relationship between age and BUA, $r = -.38$, $p < .05$, and between age and knee extension torque $r = -.37$, $p < .05$. BUA was also significantly associated with knee extension torque, $r = .49$, $p < .01$.

With the increase of age, there tended to be a decrease in the loading dose of vigorous activity in 2–4 and 4–6 Hz frequency bands, $p < .1$ (Table 2). The increase of loading dose in all three frequency bands in moderate or vigorous activity was associated with higher BUA, $p < .05$. However, there was no association between BUA and loading dose in very light or light physical activity, $p > .05$. The increase of loading dose in all frequency bands in light, moderate, or vigorous activity was associated with higher knee extension torque, $p < .05$, while loading dose in very light physical activity was not associated with knee extension torque $p > .05$.

Discussion

To our knowledge, this is the first study that has assessed the loading dose of physical activity in both different intensity and frequency ranges. Our results showed that loading dose was associated with muscle strength and bone density in middle-aged women. However, this association only existed for physical activities above certain intensity threshold: BUA was only associated with loading dose of moderate and vigorous physical activities, while knee extension torque was associated with loading dose of light, moderate, and vigorous physical activities. When intensity of physical activity surpasses these thresholds, loading frequency also becomes important as loading dose in all frequency bands was related to BUA and knee extension torque. Our results also showed that with ageing there tended to be a preferential loss of loading dose in high frequency bands of vigorous activity.

The methodology employed in the current study is novel as it enables the examination of the loading dose in different intensity categories and frequency bands on physical activities performed in natural environment. Previous studies have used methods such as acceleration counts [13,14], magnitude of acceleration [15–17], and time spent at different intensities of physical activities [18,19] to assess physical activity. However, these methods could not provide the important information on loading frequency in their assessment. In fact, our results suggest that loading frequency may be crucial as the decrease of loading dose with ageing tended to start from the high frequency bands of vigorous activity.

Both the magnitude and frequency of the mechanical signals were used in determining the loading intensity of physical activity, as both of these two parameters were found to be important determinants for bone adaptation to mechanical loading [10,20,21]. The inclusion of loading frequency is also relevant to muscle adaptation as velocity of movement in physical activity is a key component for the improvement of muscle strength and power [22]. Logarithmic function was used in the calculation of loading dose, as previous study found that prolonged exercise has a diminishing effect on bone [23].

The current study found that with the increase of age there was a significant decrease of BUA and knee extension torque in middle-aged women. This finding is supported by previous studies. Pouilles et al. [24] reported that women in the age from 45 to 66 years experienced an estimated vertebral bone loss of 0.8–2.4% per year. There is also ample evidence showing that an accelerated loss of muscle mass and strength happens after menopause [6]. The positive correlation found between BUA and knee extension torque is in line with the current understanding that muscle contraction force plays an important and positive role in bone loading [25].

Previous studies found that high impact training, especially those movements producing high strain rates and high peak forces to bone, was most effective in enhancing bone formation in premenopausal women [26]. It was also found that the bone mineral density (BMD) change at the proximal femur of premenopausal women correlated significantly with acceleration exceeding 3.6 g [15]. These findings support our results in this study that only loading dose in moderate and vigorous activities are significantly associated with BUA. Unlike BUA, the current study found that loading doses of light, moderate, and vigorous activities were all associated with knee extension torque. This is in agreement with a previous study showing that a high intensity, low repetition training protocol and a low intensity, high repetition training protocol could both effectively improve muscular strength and size in middle-aged women [27]. Similar to our results, Vanni et al. [28] also found that low intensity exercise does not affect bone growth or metabolism in premenopausal women but does improve muscle strength and function. These findings have an important implication as they show that menopausal women can still gain dramatic improvements in muscular strength with low intensity physical activity.

The current study found that only a very short period of time was spent on moderate and vigorous activities, and about half of the participants did not have any moderate or vigorous activity in the 10-hour recording time. These results are comparable to previous findings that high impact loading (acceleration magnitude large than 3.1 g) is rare in everyday activities [13,29]. For example, Deere et al. [13] found that for adolescent girl the median value of high impact counts was 34.9 impacts per day, while Tobias et al. [29] found that for the elderly only between one and eight high impacts were recorded for a whole week. Our study also showed that the loading dose in the high frequency bands of vigorous activity tended to decrease with ageing. This may be explained by the changes in the mobility profiles associated with ageing, which include both reduction in vigorous activities [13,29] and decrease in the movement speed in physical activity [30]. Both changes could alter the mechanical loading in the frequency domain by reducing the high frequency content of ground reaction force [31], leading to the decrease in loading dose specifically in the two high frequency bands as found in this study. It should be noted that mechanical loading at frequency higher than 6 Hz could also be osteogenic [12,32], and might be reduced with the changes in mobility described above

Table 1
Duration of physical activity in different loading intensity categories Note: *p < .05 compared with loading intensity category of 10–15 and >15 BW/s, ¶p < .05 compared with intensity category of 5–10 BW/s.

Loading intensity category (BW/s)		Very light (<5)	Light (5–10)	Moderate (10–15)	Vigorous (>15)
Duration of physical activity (s)	Median	35,647.5*¶	250.0*	7.5	0
	25th	35,095.0	70.0	0	0
	75th	35,876.3	651.3	51.3	6.3

Table 2
Correlation coefficient (Kendall's τ) between loading dose and age, BUA, and knee extension torque (n = 34).

Loading intensity category	Loading dose	Age (year)	BUA (dB/MHz/kg)	Knee extension torque (N·m/kg)
Very light (<5 BW/s)	*LD_B1*	−.11	.12	.17
	LD_B2	−.07	.08	.11
	LD_B3	−.15	.23	.17
Light (5–10 BW/s)	*LD_B1*	−.16	.16	.30*
	LD_B2	−.17	.15	.31*
	LD_B3	−.17	.17	.32**
Moderate (10–15 BW/s)	*LD_B1*	−.15	.27*	.45***
	LD_B2	−.19	.30*	.44***
	LD_B3	−.17	.28*	.45***
Vigorous (>15 BW/s)	*LD_B1*	−.21	.36**	.44***
	LD_B2	−.22+	.40***	.43***
	LD_B3	−.22+	.41***	.45***

+ $p < .1$.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

[31,33]. However, the loading dose above 6 Hz was not analysed in the current study because the acceleration signal was filtered at the cut-off frequency of 6 Hz. This was necessary to ensure reliable measurement of acceleration as signals above 6 Hz was likely to be contaminated by noise due to skin deformation [11]. As loading in the high intensity categories and frequency bands had the strongest association with BUA and knee extension torque (Table 2), our results suggest that middle-aged women might be at the risk of losing the beneficial effects of mechanical loading in high frequencies. It may be necessary to design novel intervention to provide such signals.

The current study has its limitations. Although moderate to strong correlations were found between loading dose, muscle strength and bone density, no causal relationship can be determined due to the cross-sectional study design. The sample size is also small, but sufficient for the purpose of this study. Another limitation is that the accelerometer could only record a maximum of 10 h. This limited the measurement of physical activity to the hours from 9 am to 7 pm in a typical weekday. Future studies may use longer duration of recording (e.g. one week) to provide more comprehensive information of physical activities. In spite of these limitations, the novel method used in this study may potentially be used as a powerful tool to monitor the administration of exercise programme, and to provide useful feedback about the loading intensity and frequency of physical activity required to bring about positive effects.

Conclusions

Association was found between loading dose of physical activity, BUA and knee extension torque in middle-aged women. However, this association only existed when loading intensity reached certain threshold level. Loading doses in all frequency bands were associated with BUA and knee extension torque when loading intensity surpassed the thresholds. With the increase of age there tended to be a preferential loss of loading dose in high frequency bands of vigorous activity. Physical activity, especially that at high intensity and high frequency levels, may have beneficial effect on muscle strength and bone mineral density in middle-aged women.

References

[1] Bonjour JP, Theintz G, Buchs B, Slosman D, Rizzoli R. Critical years and stages of puberty for spinal and femoral bone mass accumulation during adolescence. J Clin Endocrinol Metab 1991;73:555–63.
[2] Kell RT, Bell G, Quinney A. Musculoskeletal fitness, health outcomes and quality of life. Sports Med 2001;31:863–73.
[3] Doherty TJ. Invited review: aging and sarcopenia. J Appl Physiol 2003;95:1717–27.
[4] Frost HM. On our age-related bone loss: insights from a new paradigm. J Bone Miner Res 1997;12:1539–46.
[5] Wilmore JH. The aging of bone and muscle. Clin Sports Med 1991;10:231–44.
[6] Maltais ML, Desroches J, Dionne IJ. Changes in muscle mass and strength after menopause. J Musculoskelet Neuronal Interact 2009;9:186–97.
[7] Borer KT. Physical activity in the prevention and amelioration of osteoporosis in women: interaction of mechanical, hormonal and dietary factors. Sports Med 2005;35:779–830.
[8] Walsh MC, Hunter GR, Livingstone MB. Sarcopenia in premenopausal and postmenopausal women with osteopenia, osteoporosis and normal bone mineral density. Osteoporos Int 2006;17:61–7.
[9] Akune T, Muraki S, Oka H, Tanaka S, Kawaguchi H, Nakamura K, et al. Exercise habits during middle age are associated with lower prevalence of sarcopenia: the ROAD study. Osteoporos Int 2014;25:1081–8.
[10] Turner CH. Three rules for bone adaptation to mechanical stimuli. Bone 1998;23:399–407.
[11] Kelley S, Hopkinson G, Strike S, Luo J, Lee R. An accelerometry based approach to assess loading intensity of physical activity on bone. Res Q Exerc Sport 2014;85:245–50.
[12] Hsieh YF, Turner CH. Effects of loading frequency on mechanically induced bone formation. J Bone Miner Res 2001;16:918–24.
[13] Deere K, Sayers A, Davey Smith G, Rittweger J, Tobias JH. High impact activity is related to lean but not fat mass: findings from a population-based study in adolescents. Int J Epidemiol 2012;41:1124–31.
[14] Rowlands AV, Stiles VH. Accelerometer counts and raw acceleration output in relation to mechanical loading. J Biomech 2012;45:448–54.
[15] Jamsa T, Vainionpaa A, Korpelainen R, Vihriala E, Leppaluoto J. Effect of daily physical activity on proximal femur. Clin Biomech (Bristol, Avon) 2006;21:1–7.
[16] Deriaz O, Najafi B, Ballabeni P, Crettenand A, Gobelet C, Aminian K, et al. Proximal tibia volumetric bone mineral density is correlated to the magnitude of local acceleration in male long-distance runners. J Appl Physiol 2010;108:852–7.
[17] Ahola R, Korpelainen R, Vainionpaa A, Jamsa T. Daily impact score in long-term acceleration measurements of exercise. J Biomech 2010;43:1960–4.
[18] Sardinha LB, Baptista F, Ekelund U. Objectively measured physical activity and bone strength in 9-year-old boys and girls. Pediatrics 2008;122:e728–36.
[19] Janz KF, Gilmore JM, Levy SM, Letuchy EM, Burns TL, Beck TJ. Physical activity and femoral neck bone strength during childhood: the Iowa Bone Development Study. Bone 2007;41:216–22.
[20] Rubin CT, Lanyon LE. Regulation of bone formation by applied dynamic loads. J Bone Joint Surg Am 1984;66:397–402.
[21] Burr DB, Robling AG, Turner CH. Effects of biomechanical stress on bones in animals. Bone 2002;30:781–6.
[22] Pojednic RM, Clark DJ, Patten C, Reid K, Phillips EM, Fielding RA. The specific contributions of force and velocity to muscle power in older adults. Exp Gerontol 2012;47:608–13.
[23] Umemura Y, Ishiko T, Yamauchi T, Kurono M, Mashiko S. Five jumps per day increase bone mass and breaking force in rats. J Bone Miner Res 1997;12:1480–5.
[24] Pouilles JM, Tremollieres F, Ribot C. The effects of menopause on longitudinal bone loss from the spine. Calcif Tissue Int 1993;52:340–3.
[25] Burr DB. Muscle strength, bone mass, and age-related bone loss. J Bone Miner Res 1997;12:1547–51.
[26] Heinonen A, Kannus P, Sievanen H, Oja P, Pasanen M, Rinne M, et al. Randomised controlled trial of effect of high-impact exercise on selected risk factors for osteoporotic fractures. Lancet 1996;348:1343–7.
[27] Bemben DA, Fetters NL, Bemben MG, Nabavi N, Koh ET. Musculoskeletal responses to high- and low-intensity resistance training in early postmenopausal women. Med Sci Sports Exerc 2000;32:1949–57.

[28] Vanni AC, Meyer F, da Veiga AD, Zanardo VP. Comparison of the effects of two resistance training regimens on muscular and bone responses in premenopausal women. Osteoporos Int 2010;21:1537–44.
[29] Tobias JH, Gould V, Brunton L, Deere K, Rittweger J, Lipperts M, et al. Physical activity and bone: may the force be with You. Front Endocrinol (Lausanne) 2014;5:20.
[30] Schimpl M, Moore C, Lederer C, Neuhaus A, Sambrook J, Danesh J, et al. Association between walking speed and age in healthy, free-living individuals using mobile accelerometry—a cross-sectional study. PLoS One 2011;6:e23299.
[31] Stergiou N, Giakas G, Byrne JB, Pomeroy V. Frequency domain characteristics of ground reaction forces during walking of young and elderly females. Clin Biomech (Bristol, Avon) 2002;17:615–7.
[32] Rubin CT, McLeod KJ. Promotion of bony ingrowth by frequency-specific, low-amplitude mechanical strain. Clin Orthop Relat Res 1994:165–74.
[33] Turner CH, Yoshikawa T, Forwood MR, Sun TC, Burr DB. High frequency components of bone strain in dogs measured during various activities. J Biomech 1995;28:39–44.